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Microgrids: Energy management by strategic deployment of DERs—A comprehensive survey

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ABSTRACT

Present paper reports the survey on existing research literatures in connection with various energy management issues/benefits of a microgrid arising due to strategic deployment of its DERs. Survey on regulatory issues includes various barriers, incentives, standards (IEEE 1547, UL-1741, etc.), environmental issues, ancillary services and metering. Economic benefits, like improvement of bus voltages, line loss reduction, deferral of upgrade, waste heat utilization, reduction of customer interruption cost (CIC), ancillary services, emission reduction, fuel cost minimization, etc. have been surveyed from many researchers' literatures in relation to methods of analyses, algorithms used and their quantification. A brief survey of researchers' opinion on DER technologies in their respective economic analysis has also been included. This paper also reviews the researches and studies on tariff structure, market strategy of microgrid energy (both electric and thermal).

Contents

1. Introduction

A better way to realize the potential of microgrid is to take a step-by-step journey from central generating system to microgrid via distributed generation. Central power generating system is, mainly, fossil fuel-based monopolistic vertically integrated 3-tier system. Fossil fuel is alarmingly scarce in reserve and an environmental pollutant. Also, at least 50–70% of the energy content of the fuel is lost as waste heat into the environment. Vertical integration of its 3-tier systems (i.e. generation, transmission and distribution), ageing of its equipments as well as highly complex of its infrastructure are prone to black-outs, like August 2003 in North America and November 2006 in Pan-European. Moreover, about 8% of generation

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is lost in the transmission and distribution network, but 7% in Great Britain. Lastly, high economic risk of massive capital involvement as well as regulatory obstacle of its monopolistic market proves to be increasingly difficult in building new large power stations [1–3].

In today's competitive deregulated and rapidly evolving market, the new paradigm of distributed generation (DG) is gaining greater technical and economic importance across the globe as it overcomes all the above-mentioned short comings of central station in addition to catering to demand growth. DG is a small, modular and on-site generating system. Black start function of DG can minimize down times and aid the power restoration procedure of the bulk distribution system. The Energy Saving Trust of UK concluded that microgeneration technologies in individual home would reach at 25% of current UK electricity demand in 2050. The increasing penetration of these DGs as well as their different ownership and independent operation might create different operating conditions within the network, namely, reverse power flow, excessive voltage rise, increased fault levels, harmonic distortion and stability problem. High degree of penetration of DG (more than 20%) as well as their siting and sizing have considerable impact on operation, control, protection and reliability of the existing power utility. Currently available technical recommendations viz., G83/1, G59/1, IEEE 1547, CEI 11-20, prescribe mandatory incorporation of anti-islanding feature to inverter-interfaced DGs for ensuring personnel safety at the grid end and to prevent any out-of-synchronism reclosure [4–8].

On the other hand, the microgrid concept enables high penetration of DG without requiring re-design or re-engineering of the distribution system itself. It is a locally operated 2-tier decentralized generation-distribution systems. Its cluster of loads and distributed energy resources (DERs), operating as a single controllable entity, overcomes above drawbacks of independent DG operation. An illustrative microgrid construction has shown in Fig. 1. MGCC (microgrid central controller) is at the head of hierarchical control system. Second level of controllers in hierarchy is load controller (LC) and DER controllers (GC). The connection point of microgrid to utility is called point of common coupling (PCC),

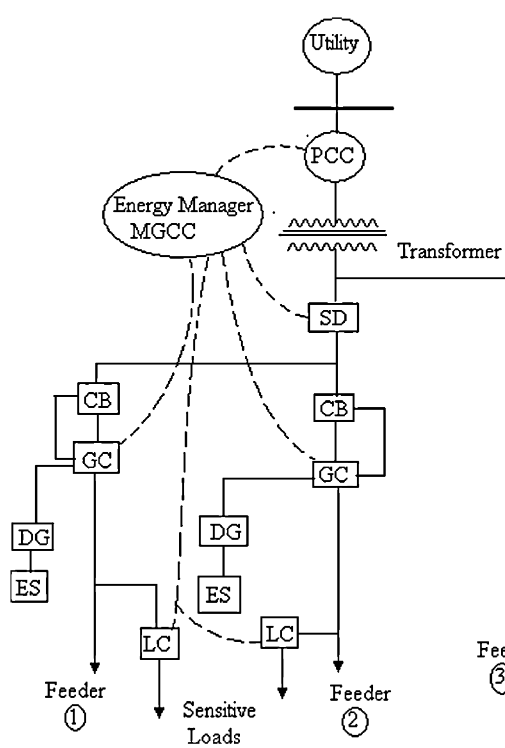

Fig. 1. An illustrative microgrid [5,14,15].

which is on the primary side of the transformer and at this point the microgrid must meet the prevailing interface requirements, such as defined in draft standard IEEE P1547. High speed LV circuit breaker (CB) or static switch is used to island it from upstream network, which is called the separation device (SD). MGCC exchanges messages in the form of data with LC and GC through communication link, as shown by the dotted lines. Messages include set points of GC and LC, monitoring of demand-supply balance and efficient operation planning of DERs [9–13].

Major investment in a microgrid is on its DERs. DERs include electric-only resources like solar PV, wind generators, small hydro, etc., thermal-only resources like solar thermal, etc. as well as combined heat and power (CHP) resources like microturbines, reciprocating engines, gas turbines, etc., of sizes a few kW to 10 MW, and energy storages of both thermal and electric types. When energy management of microgrid is done by strategic deployment of these DERs, benefits like, enhancement of power quality and reliability (PQR) of supply to the customers, reduction of network losses, increased efficiency through waste heat utilization, reduction of emission and deferral of investment in new generators as well as distribution system up gradation, etc. can be achieved. Energy management system (EMS) makes decision for production and dispatch of electric power and heat based on load profiles (both electric and heat), weather, price of electricity and heat, cost of fuel, environmental regulations, and local government policies. Thus, energy management encompasses techno-economic issues, which dictate how efficiently optimal investment planning in siting, sizing and technology selection of DERs could bring best PQR of supply to the customers at optimal price. The objective of the energy management is to attain an economically feasible microgrid and so it has a broad role to play in maximization of above benefits [1,14–16].

The present paper includes a survey on previous research works, which have addressed all the economic aspects of energy management arising due to strategically deployment of DERs. The survey is organized into six sections. Following Section 1 on "Introduction", Section 2 discusses on "Regulatory issues/framework", Section 3 reports on "Economic benefits", Section 4 surveys on "Tariff/incentive structures", Section 5 reviews on "Market strategy", and lastly, Section 6 draws "Conclusion".

2. Regulatory issues/framework

Regulatory framework includes a set of principles, rules and incentives, which addresses sensibly both technical and economic issues of DERs connections to microgrids. Technical issues encompass new standards of DG technologies, interconnection practices, protection schemes, environmental issues, ancillary services and metering. On the other hand, economic issues deal with various incentives, tariff structures and other financial obligations to stimulate the growth of microgrid. Before framing the regulatory structure, it is important to know the barriers to the interconnection of DERs as well as microgrid with distribution network. The most commonly cited barrier is relatively high connection cost of DER to distribution network due to deep connection charge policies. Other barriers are: (1) high capital cost of DERs – mainly for renewable resources (RESes), (2) non-uniform regulatory requirements, (3) lack of experience with DERs – mainly in competitive market, and (4) lack of incentives/reward to distribution system operators (DSO)/distribution network operators (DNO) for new investment – utilities have a considerable economic disincentives to embrace DERs [16,17].

Microgrid is stipulated to manage energy by strategic deployment of its DERs in both grid-connected as well as islanded modes to enhance PQR of supply to the customers. During islanding utility's responsibilities of voltage and frequency regulation are taken

over locally by DERs. Thus, islanding creates conflict with the existing grid codes and regulations. It also raises safety and damage liability issues. All existing European codes force immediate disconnection of DERs (i.e., anti-islanding) during blackouts to prevent potential safety threats to other network users and utility field operators as well as to avoid operation and protection complexities. In US, as per IEEE 1547 guide, DERs are required to detect unintentional islanding and cease to energize the area within 2 s of island. Currently drafted guide, IEEE P1547.4, permits intentional islanding of microgrid. European Union (EU) allows intentional islanding of a specific private installation from the utility to improve its own PQR. IEEE P1547.4 is applicable for interconnection of all sorts of DERs, whereas UL-1741 standard is recommended for interconnection of PV and other inverter-based DERs. In Japan, regulatory issues framed by the Ministry of Economy, Trade and Industry (METI) include grid-interconnection of DER on the first-cum-first-served basis but do not tell anything about social optimum penetration of DERs [17–23].

Apart from interconnection issues, environmental regulation issues are vital with respect to DER deployment. With a significant emphasis on climate change policy, EU promotes low carbon generation technologies and RESes with a new binding target of a “20% renewable portfolio standard by 2020”. To comply with the Kyoto protocol and to reduce green house gas emission, presently all the countries, like US and EU, are enacting the “Clean Air Act” and this legislation regulates the level of emission produced by various types of machineries. In CHP-based microgrid, the responsibility of EMS is to schedule the operation of DERs on the basis of emission reduction. DER units both reduce and displace emission from central electric power generation and from local heat generation. The California Environmental Protection Agency (EPA) Air Resource Board (ARB) has recommended emission cap that are based on the rating of DERs. 0.5 lb/MWh NOx cap is California’s permitting standard for small-scale stand-by generation. Best Available Control Technology (BACT) has been mandatory for combustion type of DERs but due to emerging technology of microturbines with smaller sizes (30–75 kW) and emission below the permitting threshold, use of BACT has been made optional. EU and US have left the smaller installations essentially unregulated, except for product standard [1,24,25].

A more stringent environmental legislation will lead to operational levies on fossil-fueled generation or prohibit their operation altogether [10].

In the current regulatory practice, metering is another important issue. Netmeter with both-way registering capability is to be installed at the PCC along with sophisticated metering tools to support the participation of microgrid in the market [18].

3. Economic benefits

Energy management planning by strategic deployment of DERs in a microgrid involves identification of the best DERs along with its size, location, manner of interconnection to the system and schedule of deployment [1]. Proper planning may bring forth important benefits of different nature as mentioned below.

3.1. From optimal siting and sizing of DERs

Improvement of bus voltages (Section 3.1.1), line flow reduction (Section 3.1.2), which includes line loss reduction, operation within thermal capacity limits of lines, reduction of internal system congestion and deferral of investment in distribution line up-gradation, and reduction of utility injection (Section 3.1.3), i.e. deferral of investment in generation augmentation as well as reduction of congestion in utility network.

3.2. From optimal technology selection

Waste heat recovery (Section 3.2.1), reliability enhancement, i.e. reduction of Customers Interruption Cost (CIC) (Section 3.2.2), ancillary services (generation adequacy) (Section 3.2.3), emission reduction (Section 3.2.4), and fuel cost minimization (Section 3.2.5). As different types of DERs have different technological as well as pollution characteristics, the economic success of microgrid depends largely on the deployment of DER-mix. CHP-based DERs, i.e. microturbines, fuel cell, diesel generators, etc. provide predictable amount of generation whereas generation from RESes, e.g. solar PV, wind generators, etc. are unpredictable due to their dependence on weather parameters. That is why energy storage is used in conjunction with RESes to ensure a predictable amount of generation. A brief literature survey on researchers’ opinion on DER technologies in their respective economic analysis has been included in separate Section 3.3 [7,10,14,26].

Translation of the above benefits into economic terms would encourage microgrid owners in future investment. In this context, authors of Ref. [10] have prepared a model to quantify some of these economic benefits. Many researchers have assessed how these benefits or part of them could be maximized with the minimum deployment cost of DERs. A literature survey in relation to above benefits has been addressed in the following sub-sections.

3.1.1. Improvement of bus voltages

In the present digital era, power quality (PQ) problems, such as voltage sag, have a huge economic impact [1]. Voltage sags that last only one or two cycles are now classified as outages. A 10% voltage sag would amount to an interruption. In this context, system average r.m.s. variation frequency index (SARFI) is used to consider the number of phases affected by sag and the duration category as per IEEE 1159 [25].

Injection of active power from a particular DG installation helps to improve the voltage profile of the network. Improvement of voltage at a particular bus helps to reduce currents in feeders downstream of the DG and play an important role in the case of large upgrade investment [27].

Authors of Ref. [28] quantified the benefits of voltage improvement using the impacts on the lifetime of a tap-changer transformer by a 500 kW solar plant.

3.1.2. Line loss reduction

System loss reduction is the most important benefit. Thus maximum attention should be paid to the siting and sizing of DG units because their installation in non-optimal locations can result in an increase in power loss in the network, because this loss displays a U-shaped trajectory [10]. Optimal siting of DG on a feeder depends greatly on the load distribution along the feeder. At the best location with nearly 10% difference in capacity addition, there is a change of loss from worst to best value [29]. Marginal losses are higher and may reach upto 30% at the extreme edges of the network [2].

For identification of optimal locations and selection of optimal sizes different tools have been used by researches in their works. Optimal locations of DERs in the microgrid have been selected using loss sensitivity indices based on either Newton–Raphson load flow method [30,31] or B-coefficients [29]. Tabu search (TS) and simulated annealing (SA) are found to be suitable for finding the optimal allocation and size of DERs from a viewpoint of loss minimization [32]. But when compared, results of TS are reported better than those of SA. Also, PSO and evolutionary programming (EP) [33], simple genetic algorithms (SGA) as well as evolutionary approach (EA) [34] have been tried, in pair, successfully to find the optimal sizing based on loss minimization. PSO is found to be better than EP with respect to results as well as time of convergence. SGA can achieve global optimum through

directional irregular searching but has several drawbacks such as excessive convergence time and premature convergence. EA overcomes the drawbacks of SGA making convergence time and stability better.

For energy management by strategically located DERs, the utility would save electricity purchases that would otherwise have been lost within the network in the form of heat. In most European countries, DNOs are responsible or mandated to keep losses at low levels. They are rewarded for loss reduction and penalized for increase the same beyond the target value [16]. In Portugal often losses are allocated to network users, i.e. customers, through the use of loss adjustment factors (LAF), which are usually defined for different voltage levels and for different periods. In Spain and Portugal regulation have a hybrid approach that rewards for reduction of losses below a standard level, while requiring increases to be purchased from energy pool [2].

Reduction of losses is the indirect benefit [14] and need to be translated into an economic terms [10]. Authors of Ref. [10] quantified economic benefits to the utility during peak load period, ranging between 0.25 cent/kWh and 0.84 cent/kWh for the specific load reduction factor of 2%. Utility requires to provide less generation to meet the losses. Owners of the microgrid enjoy this benefit as an incentive paid by utility at an electricity-selling price [14] or cost for power [35].

3.1.3. Deferral of upgrade

Especially due to load growth a few feeders of distribution network is heavily congested at peak demand hours. As per the network topology, distribution utilities (DU)/DNO is required to upgrade a large part of the network to relieve those overloaded feeders which becomes a costly proposition. Again, in metropolitan areas, upgradation for load growth by investment on new transformers or by installation of new distribution feeder is extremely costly [10,27].

Microgrid, with its local generation facility, reduces power flow in the feeders and ultimately postpones the need to upgrade some overloaded feeders. The ability of DG to defer the investments of expanding or upgrading the distribution system is usually dependent on network condition and characteristics of DG units [27]. Most important deferral benefits are obtained when DGs are installed at the end of long feeders and near the load pockets. But level of deferment strongly depends on the location and size of the DG.

Regulators insist the DU/DNO to include DG within their business plan as a "non-wires" solution to network upgrades [36]. Safety and security standard was a major driver of network upgrade and the level of security to be contributed by DG plays a large role in allowing investment deferral. In UK security standard ER P2/6 specifies contribution factors, known as "F-factors", to determine the contribution of DG plant based on capacity and types, such as intermittent (e.g. wind power) and non-intermittent (e.g. CHP plant).

For a generic microgenerator technology, the value of reduction in peak load growth is a function of its regime of generation at peak time [16]. In Portugal, peak load of T&D networks occurs during night of a winter day, the PV systems tend to have no contribution for deferral of T&D load-growth-related investment while the micro-CHP systems tend to have higher contribution. Costa et al. [16] suggested the inclusion of the uncertain climatic effect on microgenerator using probability density function in the formulation of unitary avoided cost function resulting from network investment deferral. Multilayer multiperiod optimal power flow method has been used in Ref. [37] for analyzing DNOs preference for siting and sizing of DG installation. Successive elimination method together with multistage planning analysis has been used in Ref. [36] respectively for evaluation of capacity upgrade and for the necessary schedule of investment.

DGs operating at peak load may create important savings by helping to avoid immediate upgrade investments, which can reach up to 20 ¢/kWh of DG output or even more. It is also the European Directive requirement for DNOs to consider the use of DG as a means of supplementary network capacity.

Quantification of deferral benefit is obtained as $ 1200/kVA [27].

3.2.1. Waste heat recovery

Microgrid is intended to cater to both electrical and thermal demands to its customers. These two demands follow two separate profiles and there is hardly any concurrency between them. Thus, energy management system (EMS) of microgrid is to be designed at the time of project planning. It should be decided then whether to track electrical demand profile or thermal demand profile in order to deploy the DERs strategically. As heat transportation, like electricity, is not feasible, EMS gives more emphasis in the co-ordination between heat demand and scheduling of DERs. Then waste heat recovered from the operating DERs are utilized efficiently to meet customers heat demand. Plug-and-play model of DERs facilitate their placement near the heat load, thereby allowing better use of waste heat without complex heat distribution systems such as steam and chilled water pipes for heating, ventilation and air conditioning (HVAC) equipments [4]. HVAC equipments, mainly, function at peak load hours when electricity price is high. Utilization of waste heat of DERs replaces the use of these equipments and lowers the costly peak power requirements [1,4,30,38].

Distributed Energy Resources Customer Adoption Model (DER–CAM) software determines that optimal selection of distributed generation and heat recovery equipment lowers overall energy costs by about 15% depending on the type of tariff. Further reduction of 1% is possible if the heat recovery equipment is selected independent of generator [38]. Investment in CHP-based DER will be cost effective as long as the cost of electricity (COE) produced by the DER plus the savings in heat demand (if any) is lower than the rates paid to the utility [10].

With a 10 kW domestic CHP unit for space heating and hot water, case studies demonstrate that 20–30% saving in energy bill can be achieved, if domestic CHP is compared with an ordinary boiler and break even period (BEP) of investment is about 5–10 yr depending on the cases, e.g. good insulated house needs longer BEP [17].

Hernandez-Aramburo et al. [39] proposed a penalty for the excess heat generated being released into the atmosphere and this function was defined as the square of the difference between the required heat and the delivered heat divided by an arbitrary scaling factor (equal to 50 for the particular example as authors of Ref. [39] cited).

3.2.2. Reliability enhancement (reduction of customer interruption cost (CIC))

Refs. [7,15,17,24,35,40–42] address reliability improvement by DG deployment in the distribution network. Costa et al. [7] discussed the co-ordinated activity of distribution management system (DMS) among LV distribution network, microgenerators, loads and storages to utilize the ability of microgrid to improve the reliability performance of distribution system. Authors of Ref. [7] also discussed the influence of different generation-to-load ratio (GLR), voltage profile and ampacity of the network on the reliability of customers. Zoka et al. [15] have used linear programming technique for optimal operation of DERs, like fuel cells, energy storage and heat sources. Authors of Ref. [15] evaluated the power interruption cost (PIC) as equivalent cost to customers' damages caused by power interruption and showed that PIC became almost zero with microgrid formation, whereas assumed high value without deployment of

DERs. Pudjianto et al. [17] discussed the quantification of the value of benefit of islanding of microgrid in terms of reduction in customer outage costs (COCs), which was evaluated by either a Great Britain system or a load-and-cost model for different classes of customers. Pipattanasomporn et al. [24] presented a mixed integer linear programming based multi-objective optimal grid-connected DG system, in which they determined the optimal mix of on-site DG and the associated system reliability at various outage costs. Teng et al. [35] have presented a cost-benefit analysis using GA and validated with test results that benefits due to reduction of customer interruption cost (CIC) can be achieved with proper types, sizes and placement of DGs. Authors of Ref. [35] have shown the improvement of average system interruption duration index (ASIDI) with the placement of DG. They also proved that lower values of ASIDI (i.e. higher service reliability) could be achieved by higher degree of DG placement though at the cost of reduction of benefit-to-cost ratio (BCR). Vallem et al. [40] assessed the storage requirement from interruption duration distribution (IDD) curve to overcome interruption. IDD were determined using sequential Monte Carlo Simulation (MCS). Kennedy [41] used a combined generation-to-load ratio (GLR) model to preserve the correlation among disperse PV installations and the load. GLR value was compared with load curtailment coefficient to determine transition (Up/down) states. Bae el al. [42] used PV-battery combined system to supply power to the interrupted customers and equated total discharge rate of all batteries with the amount of emergency power from a PV system.

There is a provision in the regulatory framework to pay penalty to the customer if reliability standards are violated at the customer point. In general, customers are resistant to accept any decline in the reliability of supply, but at the same time are not willing to pay extra to cover the costs of any reliability improvement undertaken by local utility. This situation makes the assessment of benefits resulting from general reliability improvement a rather complex, if not impossible task [10].

3.2.3. Ancillary services (generation adequacy)

Ancillary service or reserve service is needed when the grid is under stress. In a restructured power system, market mechanism is applied in the planning of reserve capacity due to the rich interaction between generators (i.e. supply side) and loads (i.e. demand side), which, again improves the resource utilization [1]. Authors of Ref. [43] assessed worth of reserve capacity and demand for reserve from capacity outage probability distribution with fast-acting DERs and customers' aggregated demand characteristic. Due to fast-start generators, there is no customers' interruption and customer damage function (CDF) would not appear in the assessment of reserve capacity [43].

As contingency reserve, Kueck et al. [1] suggested deployment of fast-start small sized combustion turbine as the good choice because these turbines start within the required time on 90% of attempts.

Costa et al. [16] suggested MCS methodology to assess the adequacy of generation capacity with different technologies of microgenerators (micro-CHP, PV, micro-wind), taking into account cumulative probability distribution function of seasonal and daily correlations between load and generation profiles of PV and micro-wind generator.

Asano et al. [19] analyzed the feasibility of reserve provision in the context of fast-acting gas-engine driven or gas-turbine driven reserve generators. Reserve capacity depends on load profiles, season and time-of-day.

Wang et al. [44] used mixed integer linear programming for estimating optimal spinning reserve (SR) for a given commitment of the day-ahead scheduling. They aggregated the uncertainties of wind generator, PV and load to an equivalent distribution model before introducing in optimization.

In practice, only a portion of the capacity is used for reserve and depending on the type of technology used, the maximum amount of capacity reserve would vary, as referred to in Yuen et al. [45].

Hernandez-Aramburo et al. [39] suggested in their study that the power reserve is arbitrarily defined as 50% of the available power in the microgrid.

3.2.4. Emission reduction

Benefit of DERs in terms of reduction of CO_2 and other emissions results from the displaced electricity generation and from the avoided losses. For a micro-CHP system the avoided emission should be estimated taking into consideration of boiler as reference. Reference value of emission may vary with the time of use of the generation-mix in the system. As for example, with intensive use of hydroplant during winter in Portugal, emission tends to decrease [7,10]. CO_2 is called global pollutant while NOx, CO and UHC (unburned hydrocarbons) have a relatively limited radius of impact and hence called local pollutant [46]. Emissions from DERs have direct relation with load ratio. DERs are designed to operate at 100% load ratio, at which emission is much lower than that at other load ratios [47].

Using equivalent load model for partial-load behavior, Mancarella et al. [46] pointed out through their studies on two different sizes of microturbines that in specific case, high CO emission are main concern to preserve air quality standard at all loading conditions, whereas high NOx emission at low loads. CO_2 emission reduction is sensitive to DG penetration (much to RESes), upstream network emission curve, which explains at what month emission becomes maximum [48]. In rural Portuguese network (LV to HV), 20% penetration of DER reduces CO_2 emission by 2.07–4.85%, in UK scale 6.5 million tones of CO_2 emission per annum can be saved by 50 million installations of domestic CHP units [49]. From the optimal solution of CO_2 emission reduction with constraints of contracted demand with utility and battery capacity, Bando et al. [50] concluded that the larger the contracted demand of the utility grid, the lower the CO_2 emission, because the emission co-efficient of the utility grid was lower than that of the electricity from the CHP system, i.e. here, gas engines. Pipattanasomporn et al. [24] investigated the optimal mix of DGs to be installed with the presence of a NOx regulation standard. Tsikalakis et al. [49] studies their system with minimization of pollutants together with the effect of participation in CO_2 emission trading market and results showed that participation in CO_2 emission trading can offset the reduction of DER earnings while reducing CO_2 emission. Piperagkas et al. [51] studied the IEEE 30-bus system, using multiobjective PSO technique, at various percentages of CO_2 reduction. Authors of Ref. [51] have compared the cost of CO_2 reduction achieved by extended use of cogeneration units and wind power penetration for various wind power prices, while satisfying heat and electricity deviations limits and considering security. Firestone et al. [52] studied on different selected sites in three US cities based on their respective electricity prices and carbon tax. They [52] concluded that in Atlanta and Boston, where electricity prices are respectively low and moderate, a realistic carbon tax level ($100/tC) incents less than one percentage carbon reduction from no-tax case, but in California, having high electricity prices, carbon tax must exceed $400/tC before "green" DER technologies are adopted. Even at carbon tax level less than $400/tC, more than 20% carbon emissions abatement is realized when a significant subsidy towards the turnkey costs of "green" technologies is provided [53]. Hawkes et al. [54] indicated that for both high electricity price as well as high gas price scenarios, microgrid is likely to produce a positive environmental effect in terms of global warming as it decreases CO_2 emission.

3.2.5. Fuel cost minimization

Hernandez-Aramburo et al. [39] presented the optimal fuel consumption rate of the microgrid while putting constraints to fulfill the local energy demand (both electrical and thermal) and to provide a certain minimum reserve power. They [39] showed an observation that piecewise-linear power sharing brought an important fuel saving with respect to the linear scheme in the range of 15–60% of power demand, whereas optimization process brought an additional reduction in fuel consumption over a wide range of power demand. Authors of Ref. [39] concluded that a power-sharing scheme, which is aimed at maximizing the financial benefits in a microgrid, is likely to rely on a communication infrastructure.

Hawkes et al. [54] suggested that centrally-coordinated control of microgrid resources might give the best economic and environmental results. They [54] applied linear programming to minimize the equivalent annual cost (EAC) of meeting the given energy (electricity and heat) demand profiles, choosing the optimal capacities and optimal schedule of generators, storages (both electric and heat) and boiler. As EAC total annual cost of electricity, fuel and maintenance cost plus the annualized capital cost of microgrid assets at a chosen discount rate has been considered. Uncertainty of wind generation was modeled with MCS using Weibull distribution.

3.3. DER technologies

DERs are of central interest in the present paper, as energy management through their strategic deployment would help achieve several economic benefits as discussed in earlier sub-sections. The owner of the DER, or microgrid as a whole, would like to optimize the economics of his installation. In present section only those merits and demerits of DER technologies are pointed out from the literatures, which are relevant for the present work.

Pipattanasomporn et al. [24] concluded in the selection of optimal mix of on-site DG that without the emission restrictions internal combustion (IC) engines and gas turbines (GT) are the only technologies selected due to their low initial cost. Microturbines (MTs) show promise when NOx emissions are major concerns. Fuel cells (FC) are still too expensive to be selected as optimal solutions even when NOx cap is introduced [24].

Reciprocating diesel generators are best suited during peak load hours when the market price is high and are, indeed, only economically viable when used for short period (80 h/yr) [37,42]. On the other hand, gas engines cannot be used economically for such short operating durations due to their high installation costs. However, for long operational periods (e.g., 2880 h/yr and 5820 h/yr), lower cost per kWh of these DG units proves to be economically sound [37].

Preferred DG technology for investment deferral is reciprocating gas-fired engines due to their modularity, efficiency, relative adequate emission performance compared with similar diesel technologies, servicing and district fuel supply availability [10]. For ancillary service, reciprocating engines (gas or diesel) are the most suited as they come on-line or off-line whenever required by the system operator within the corresponding time scale [10]. Gas engine-driven generators can start within 2 min of instruction at a ramp rate of at least 25 MW/min [19]. Advanced lean-burn natural gas engines produce NOx levels as low as 50 ppmv and efficiencies are around 35% with a goal of 50% [4].

Widespread implementation of MTs may displace or avoid emission from polluting conventional central coal plants with a net positive environmental benefit [10]. Main advantages of MTs include sophisticated combustion systems, low turbine temperature and lean fuel-to-air ratio result in NOx emission less than 10 ppmv and inherently low CO emissions. With natural gas as well as gasoline as fuel, efficiencies of MTs lie in the range of 28–30% [4].

FCs offer higher efficiencies than MTs, but are currently expensive. CO and NOx emissions for FCs are much lower than the emissions for MTs. However, total hydrocarbon (THC) emission for FC is more than MT. Now phosphoric acid cells are commercially available in the 200 kW range [4,47].

For the same level of DG penetration, CHP and PV plants allow higher load growth before network reinforcements, than wind plants. CHP and PV energy production patterns fit better with the particular feeder load demand profile and, in addition, these technologies show less randomness than wind energy production [55]. As per Hawkes et al. [54] PV systems are never selected by the optimization model because of their high capital cost, which means they are not competitive with the other technology options. Marnay et al. [56] have modeled PV systems in DER–CAM, whereas wind technology, as per the authors of Ref. [56], is far from viable in the DER–CAM model due to highest cost with respect to others. Levelized costs of 1 kW and 10 kW wind generators are estimated to be 39.85 cent/kWh and 27.05 cent/kWh, respectively, which are higher than costs of a diesel or natural gas back-up generator or even a MT or FC [37]. For PV and wind generators the power in reserve is defined as the difference between the maximum power that could be delivered under the prevailing conditions and the power that is actually delivered [39]. Globally, Germany and Japan have dominated PV cell production and installation as a result of aggressive incentives [22].

PV system includes batteries to compensate for fluctuating output of solar radiation [10,42]. PV system should supply the electric power to the interrupted customers considering discharge rate of batteries [42]. Without storage, the solar PV, typically, contributes less than 40% of its rating towards distribution capacity [22]. Economics of storage is particularly complex, both because it requires optimization across multiple time steps and because of the influence of tariff structure [52]. Storage devices are energy limited and hence non-Markovian. From the interruption duration distribution (IDD) curve, a need-based assessment of storage is done [57].

4. Tariff structure

Tariffs have been designed to recover all costs of generation and transmission-distribution equitably among customers with similar consumption pattern. Typically, DG is most economical in applications where it covers the base load electricity and uses utility electricity to cover peak load consumption and the load during outage of DG units, i.e. as standby service [58].

Firestone et al. [58] used the tariff structure with (1) fixed charge ($/month) – intended to cover infrastructure and delivery costs, (2) volumetric charge ($/kWh) – to cover the variable costs of producing electricity, such as fuel charges and variable maintenance expenses. There are three types of volumetric charges i.e. flat, time-of-use (TOU) and real time pricing (RTP), and (3) demand charge ($/kW) – intended to collect the fixed costs of infrastructure shared with other customers in proportion to the capacity each requires. Authors of Ref. [14] formulated the benefit accrued to microgrid owner from selling of electricity to its commercial customers using fixed, volumetric and demand charges in the tariff structure. They [14] also, included standby charge of virtual utility generator, based on critical load of microgrid, as a negative benefit to owner as well as congestion charge based on peak demand as a positive benefit. They [14] examined the effects of standard and standby tariff structures on DG economics. Gil et al. [10] justified that utility bought from and paid to the DG-owner a "Customer-output tariff" for the electricity produced when rate offered by the owner of the DG for its output is lower than the wholesale electricity price paid in the spot market. This tariff covers the participating DG's cost of electricity (COE) plus a sign-up premium for enrolling in the program.

The economic benefits of DER deployment, as discussed in Section 3, deserve attention from policy-makers. Quantifications of these benefits are case specific and should be investigated separately. Asano et al. [19] discussed the tariff structure of ancillary services as consisting of two parts: demand charge and energy charge. Demand charge is based on the load adjustment contract of the utility and energy charge is based on wholesale prices of the Japan Electric Power Exchange. Imperfect reliability of DER affects demand charges and standby charges as back-up to DER would have to be provided by the utility [59].

To encourage the investment on beneficial DG or to support the installation of renewable technologies, e.g. PV, solar thermal, small wind, etc., also called "Society beneficial DG", regulators apply a fee to all electricity pool market transactions in order to raise fund. This fee is to be based on the expected quantified benefits [10].

A reasonable and fair emission tariff should be built into the market system so that electric power supplied by DER will be valued appropriately considering the net emission reduction. Tariff could even be a function of time, season and location, so that at worst pollution times and locations, the tariff would be most attractive [1]. In USA, a mitigation fee of $ 16.5/kg ($ 7.5/lb) is charged on NOx emission above the RECLAIM (Regional Clean Air Incentives Market) allocation. The funds collected is to be used to clean up dirty equipments that has so far eluded air pollution regulations to ensure permanent reduction of both smog-forming emission and cancer causing diesel soot [56].

Deconineck et al. [60] showed how introduction of smart meters becomes beneficial for implementation of new tariff schemes as well as to stimulate demand response based on price incentives when DER units are available. Authors of Ref. [60], also discussed the influence of renewable energy resources on TOU, RTP tariff schemes and on demand response.

5. Market strategy

Microgrid can participate in energy market as well as ancillary service (AS) markets. Microgrid market is oligopolistic [26] and operated by four agents – production agents, consumption agents, power system agent, and MGCC (Microgrid Central Controller) agent [61]. MGCC acts as a market operator for the controlled area of microgrid and plays the role of energy manager by coordinating various small DER units of different owners, or production agents and different categories of loads – shedable and non-shedable- or consumption agents. DER units and loads participate in the coordination process through their respective individual controllers such as generator controller (GC) and load controller (LC). Power system agent announces to all participants the selling and buying price, but does not participate in the market operation. Microgrid energy could be marketable if the benefits accrued due to energy management by strategic deployment of DER units are properly quantified as well as translated into monetary terms and afterwards, allocated to the owners as incentives [10,62].

MGCC is a software-based agent and is designed for intelligence and automatic control of both market and system operation and aims to satisfy local energy demand of both electricity and heat using optimal sharing of its local units either without grid participation, termed as "good citizen" behavior or exchanging with grid as "ideal citizen". Each DER unit has the autonomy to set the optimum level of energy, which it is willing to produce at a given market price. This price is provided by the distribution network operator (DNO)/market operator (MO)/system operator (SO) through MGCC. This flexible operation of generator relieves microgrid as well as nearby feeder from congestion by operating at the time of peak demand when electricity price is high and also helps microgrid at the time of islanding operation. Market price also influences response of the shedable or controllable customers who reduces their load at higher price [1,61,63].

Distribution utilities (DUs) or load serving entities (LSE) guarantee the electricity supply to customers by purchasing power from the wholesale market through both, long term bilateral forward contracts with generators or brokers and the short-run spot electricity market [10].

In the electricity markets, generating units are usually dispatched from the cheapest to the most expensive until the total generating capacity meets the expected demand [10].

In wholesale electricity markets, most of the demand is settled through forward long-term contracts with generators. However, there is also a remaining amount of demand that is always traded in the spot market [10].

RESes, like solar PV and wind generators are unpredictable sources of energy. They are not allowed to bid in the market and are taken into the system as and when these resources are available. But in conjunction with storage system this uncertainty of generation can be smoothed out and RESes become the responsible participant in the bidding process. Again, for natural gas dependant microgrid, PV and wind hedges against the price spike of natural gas [26,64].

DER participates in the emission trading market and emission data together with energy prices for the upstream network are communicated to the MGCC. The CO_2 remuneration takes place according to these communicated data [49].

Reserve market is based on three basic levels of reserve: (1) a short-run, spinning reserve (usually 10–30 min), (2) a short-run, non-spinning reserve (usually 10–30 min), and (3) a long-term, stand-by reserve (offline capacity ready to operate within 30 min or more). Authors of Ref. [10] suggest that current DG technological characteristics and regulatory framework make it challenging for DGs to participate in the short-run type of reserve markets. Reciprocating engines (gas or diesel) are preferred technologies as they are easily dispatchable and remotely controllable. According to market rules, a single price for each type of reserve is cleared every day, which remains constant during that day [1,10].

EMS sells the reserve service in the day-ahead market through bidding process. If bid stands, the EMS would plan to execute a contract of supplying the service the next day [1,45]. Optimal bidding into short-term AS-market is facilitated for determination of reserve for optimal microgrid operation. Authors of Ref. [45] stated that a contract in the reserve market longer than 1 hr becomes sub-optimal.

Spinning reserve, as most significant service, is sold like insurance, i.e. microgrid would be paid whether its service is called for or not and to achieve maximum benefit, market is to be settled based on bids for capacity [1,65].

As electricity could not be stored, its spot price becomes highly volatile due to change of supply and demand balance. Microgrid may profit by selling contingency reserve to the power system when spot price is high [1].

6. Conclusion

Microgrid is an emerging field in power and energy sector, though still not matured currently. Extensive research and pilot projects need to be undertaken until it can be put in the competitive market in the deregulated regime. USA, Japan and some European organizations have put some efforts into it, although it is still under the research and experimental stage.

A number of barriers for DG are listed in existing research literature, so that more radical changes may be undertaken in the regulatory framework to facilitate development of microgrid. Regulators and legislators should frame new rules and laws and make changes to existing ones so that microgrids systems can participate

and compete in a new market for energy and ancillary services. These changes can be laid down as new laws by legislators or included as amendments to the existing electricity rules by regulatory agencies.

As DERs are the major investment area of microgrid, their technological up gradation are vital to reduce the generation costs. At the same time the benefits resulting from deployment of DERs in microgrid are to be identified and properly quantified and finally, a way to share these benefits must be proposed to ensure an efficient economic microgrid. DUs in many countries consistently charge connection tariffs (fixed or variables) to the owners of DG, though DG is saving the utility considerable amounts of money every year. For instance, the benefit resulting from loss reduction may be included as an incentive in the tariff mechanism. Similarly, other benefits obtained from microgrids are to be addressed properly and should be compensated accordingly through framing of regulatory rules by regulators and policy-makers.

CHP operation of microgrids facilitates reduction of its carbon emissions. If carbon emission rules of government are stringent then microgrid's economics will be improved and more DER technologies will be deployed. Again, climate change and depleting fossil fuel reserves are main motivators for the emergence of efficient renewable and low carbon-based distributed generation technologies.

Tariff structure and market policy should be straightforward so that DG or microgrid owners can easily participate in the competitive market. Regulators should not allow tariffs to be punitive or discriminatory, and tariffs should not included stand-by fees based on installed capacity. Stand-by fees should instead be replaced by demand charges and emergency stand-by rates, which incent microgrid operators to adopt measures that are economically sensible and mutually beneficial.

Moreover, social awareness is of utmost importance, which would ultimately aid the growth of DERs and microgrids. Thus, with mass production, cost of DGs could come to economies of scale.

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